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4H SiC Lateral Single Zone RESURF Diodes

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13. ABSTRACT *(Maximum 200 words)*

Silicon Carbide is an attractive material for development of high voltage and high frequency devices. The critical electric field of Silicon Carbide is more than 10 times higher than that of Silicon and hence a larger breakdown voltage can be supported in a smaller drift length as compared to Si devices. From Si studies it is known that the breakdown voltage is low for very high and very low doses and high for intermediate doses and that it increases linearly with the RESURF length till it reaches a maximum value limited by breakdown at the epi-substrate junction. This work deals with simulations on 4H SiC RESURF diode. From our simulations, the maximum breakdown voltage that we obtained was 2240V at a dose of 1x10 to the 13th power per cm square which is around 94% of the ideal parallel plane breakdown voltage. Electric field in the oxide at such high voltages can become quite high and can lead to premature breakdown of the device. To solve this problem, we used nitride as the dielectric. The optimum dose in this case, was found to be 7 x 10 the 12th power per cm square which gave the maximum breakdown voltage of 2100 V. The electric field in nitride does not exceed 3.5 x 10 to the sixth power V/cm which is much less than the nitride rupture field of 1 x 10 to the 7th power V/cm. For both oxide and nitride cases, we obtained a good range (7x10 to the 12th power/cm square -2 x 10 to the 13th power/cm square) of dose where the breakdown voltage is quite high (2000V and above), which is not seen in Si RESURF devices.

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4H SiC Lateral Single Zone RESURF Diodes

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Introduction

Silicon Carbide is an attractive material for development of high voltage, high temperature and high frequency devices. The critical electric field of Silicon Carbide is more than 10 times higher than that of Silicon. This implies that lateral RESURF (REduced SURface Field) devices made in SiC can support the same breakdown voltage in a much smaller drift length, as compared to silicon devices [1]. Extensive work has been done on RESURF devices in Si [2-4], and though some work has been done in SiC [5], a more comprehensive analysis still remains to be done. The goal of the rest of the report is to show simulation results for RESURF diodes in SiC. The breakdown of a RESURF device depends on the RESURF layer dose and the RESURF layer length. From Si studies it is known that the breakdown voltage is low for very high and very low doses and is high for intermediate doses and that it increases linearly with the RESURF length till it reaches a maximum value limited by breakdown at the epi-substrate junction. Therefore, the RESURF layer has to be optimized for dose and length to achieve high breakdown voltages in SiC devices. In this work, the optimization was performed for the 4-H polytype.

Device Structure 1

Fig. 1 shows the cross-section of a lateral single zone RESURF diode. The basic structure consists of two p-n junctions: a vertical P^+N_{res} junction and a horizontal P^-N_{res} junction. Considering these parts as one-dimensional junctions, the vertical junction has a lower breakdown voltage compared to the horizontal junction. The doping of the P^-epi layer determines the voltage that can be supported by the device when breakdown occurs at the horizontal junction shown in Fig.1.

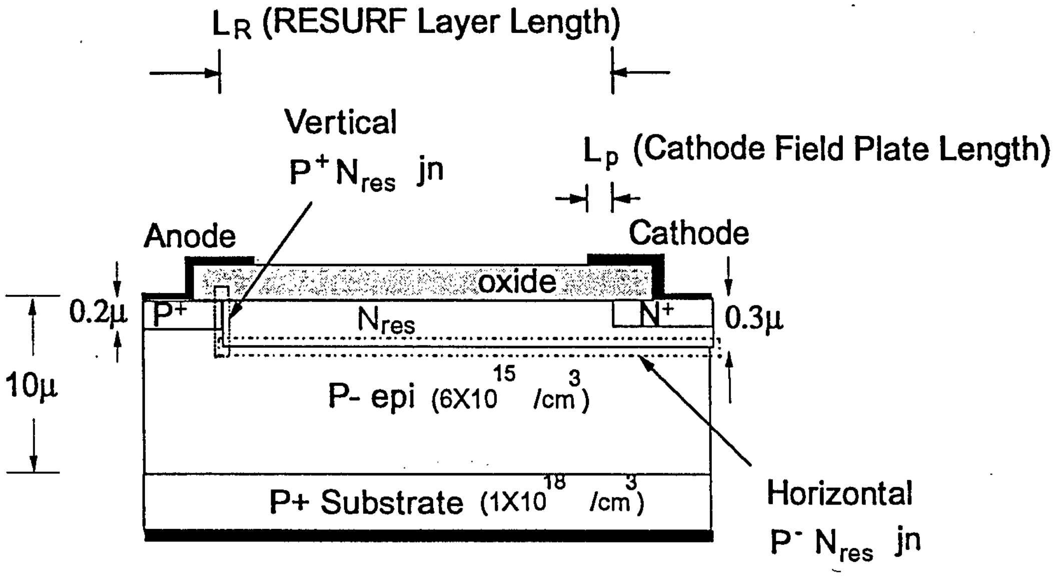

Fig 1 Cross-section of a single zone lateral SiC RESURF diode

Due to the RESURF action, the depletion of the vertical P^+N_{res} junction is reinforced by the horizontal junction. Consequently, for the same applied voltage, the depletion stretches along the surface over a much longer distance than would be expected according to simple one-dimensional calculations. As a result, the electric field at the surface is reduced and surface breakdown can be eliminated [6] The total charge in the drift region needs to be adjusted to an optimum value in accordance with the RESURF principle to achieve maximum possible breakdown voltage. Therefore, simulations were carried out for various RESURF layer doses and for different RESURF lengths. These simulation results are discussed next.

Simulation Results

To start with a 1 dimensional simulation was done, on the device simulator, MEDICI, to determine the ideal parallel plane breakdown voltage of vertical $N^+N_{res}P^-P^+$ diode formed at the cathode end as seen from Fig.1. The epi-layer thickness, RESURF layer thickness and the dopings are as shown in Fig.1 This is the maximum breakdown voltage that we can expect for our device. From the 1D simulations, the breakdown voltage was found to be 2380V. Also for the optimum case, the RESURF layer has to be fully depleted when the electric field reaches the critical electric field for breakdown at the horizontal p-n junction. Assuming a uniform electric field profile in the RESURF layer, using Gauss's law, we get the optimum charge to be

$$Q = (qN_Dt) = \varepsilon_s E_c \qquad (1)$$

where N_D is the doping of the RESURF layer, t is the thickness of the layer, ε_s is the permittivity of SiC and E_c is the critical electric field in SiC. The critical electric field is hard to determine for our structure, but as an approximation we took E_c the same as that for a n^+p junction of the same doping [7] For a p doping of 6×10^{15} /cm^3, E_c is 2×10^6 V/cm. For this value of E_c we get an optimum dose of $Q = 1.07\times10^{13}$ /cm^2.

Therefore, if the RESURF phenomena is found to work for SiC, we expect a maximum breakdown voltage of 2380V which should occur at a dose of approximately 1.0×10^{13} /cm^2.

The Single Zone RESURF diode was simulated for various doses, using the 2-D numerical simulator, MEDICI. The RESURF phenomena can be better understood by analysis of the operation in 3 regions:

Region 1: When the dose is very high, the RESURF layer does not fully deplete on the application of a high reverse bias. In this case, therefore, electric field crowding occurs at the anode end and the device breaks down due to high fields under the anode field plate much before the parallel plane breakdown is reached. The potential distributions and the electric field profile for a high dose of 3×10^{13}/cm^2 is shown in Fig. 2 and Fig. 3.

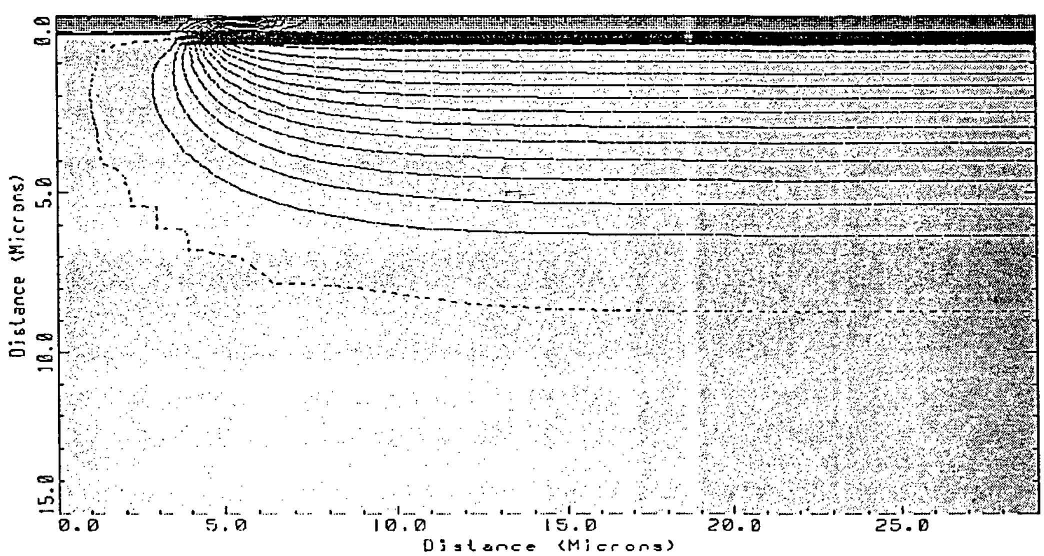

Fig 2 Potential Contours at breakdown for RESURF dose of 3×10^{13} /cm^2

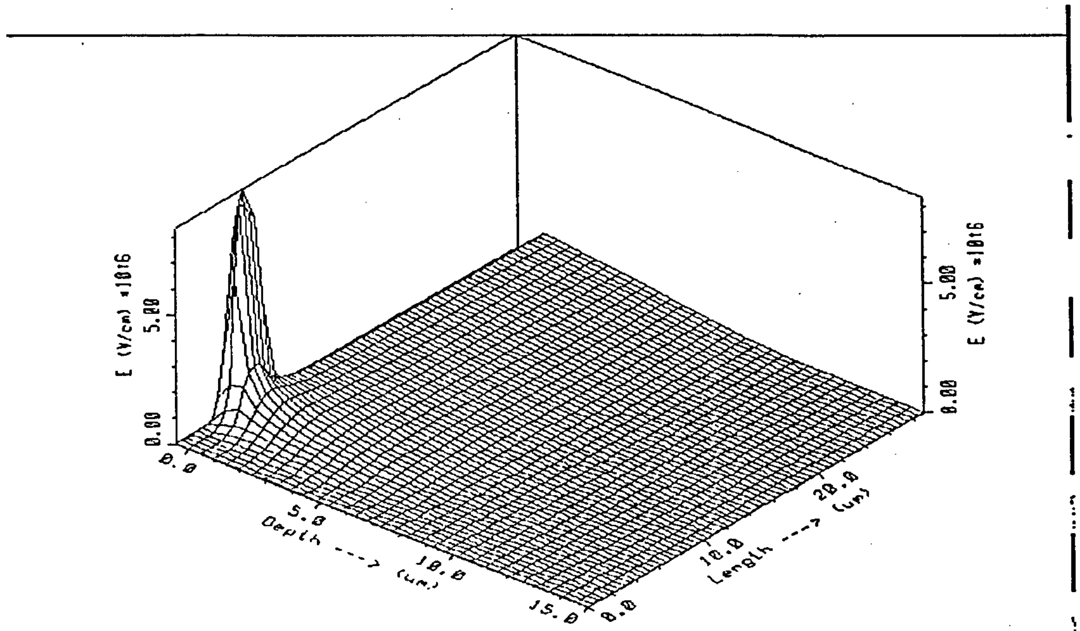

Fig 3 3-D Plot of the Electric field in the diode for a dose of $3x10^{13}$ $/cm^2$

The electric field along the surface in SiC is shown in Fig. 4. The plot clearly shows a very high electric field peak at the anode end. This is responsible for the early breakdown of the device. The 3-D potential distribution plot is shown in Fig 5. From the plot, we can see that most of the potential drop occurs at the anode end.

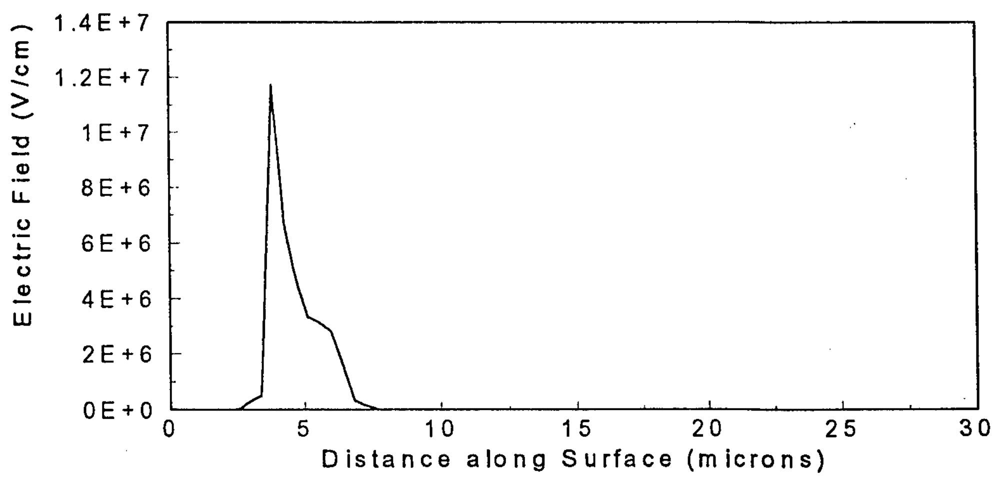

Fig 4 Electric Field Profile in the RESURF layer for a dose of $3x10^{13}$ $/cm^2$

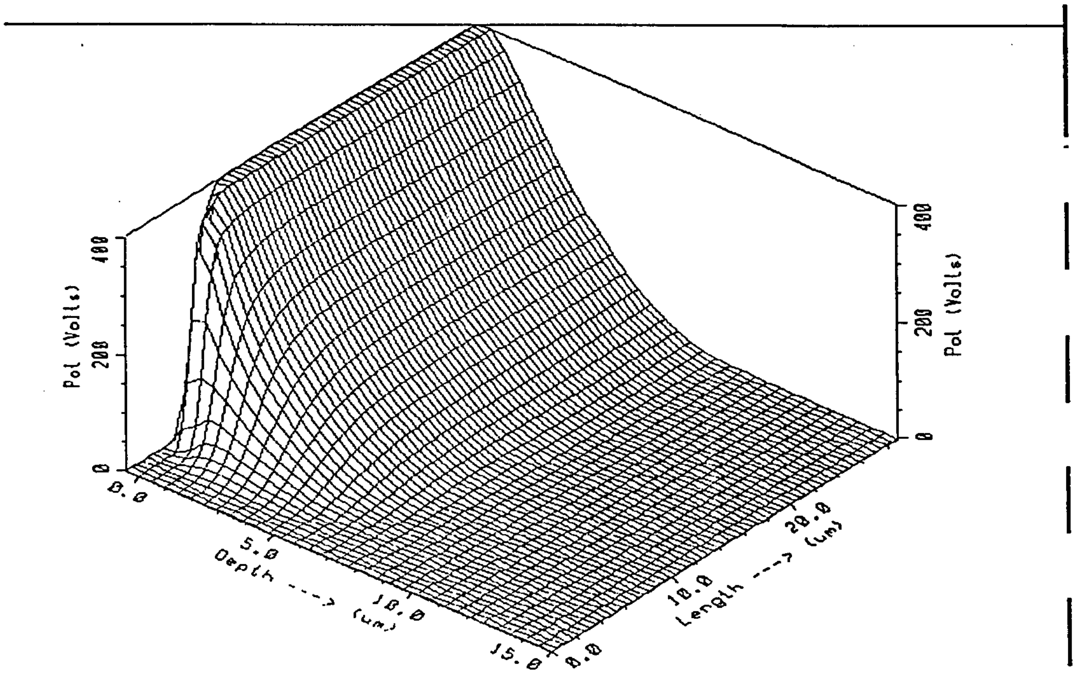

Fig 5 3-D Plot of the Potential distribution in the diode for a dose of $3x10^{13}$ /cm^2

Region 2: At very low doses, the depletion reaches the cathode end. However, due to the curvature of the N^+-N_{res} junction, electric field crowding occurs and high fields are formed at the cathode end. In this case too, the breakdown voltage is less than the optimum value. The potential distributions and the electric field profile for the low dose of $1x10^{12}$ /cm^2 are shown in Fig. 6 and Fig. 7 where the field crowding at the cathode end dominates the field crowding at the anode end.

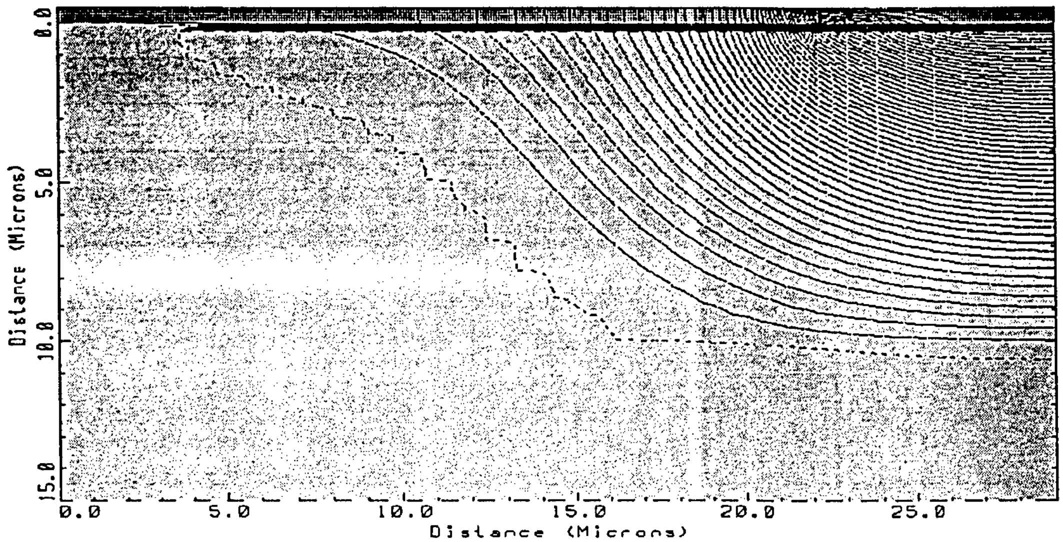

Fig 6 Potential Contours at breakdown for RESURF dose of 1x10^{12} /cm^2

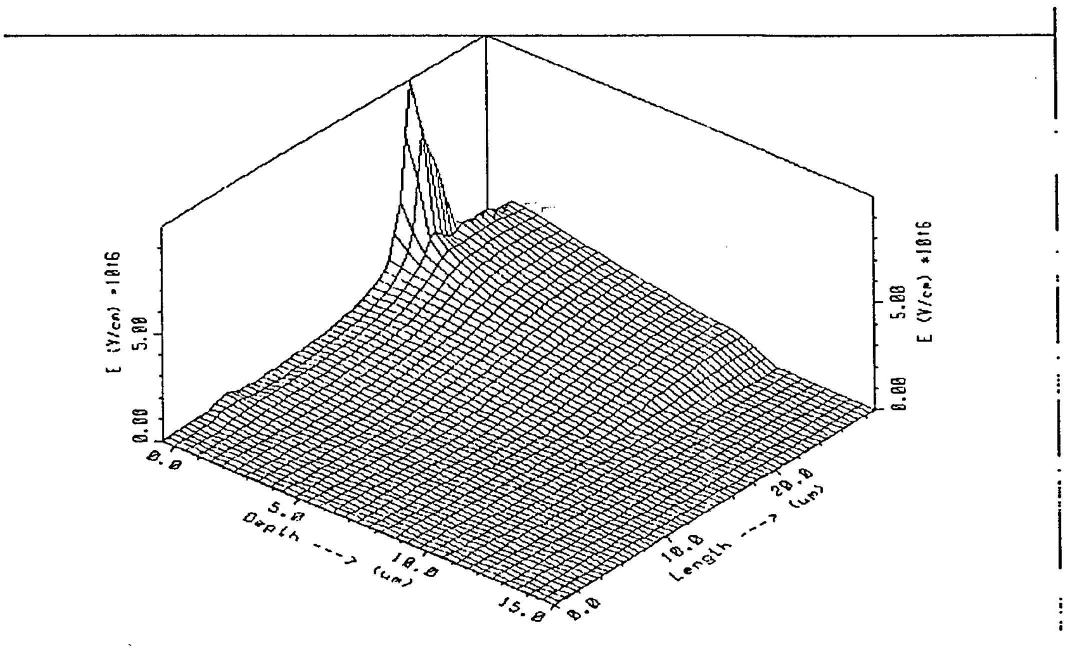

Fig 7 3-D Plot of the Electric field in the diode for a dose of 1x10^{12} /cm^2

The electric field at the surface is shown in Fig. 8. In this case, the peak electric field occurs at the cathode end where most of the potential drops as seen from Fig. 9

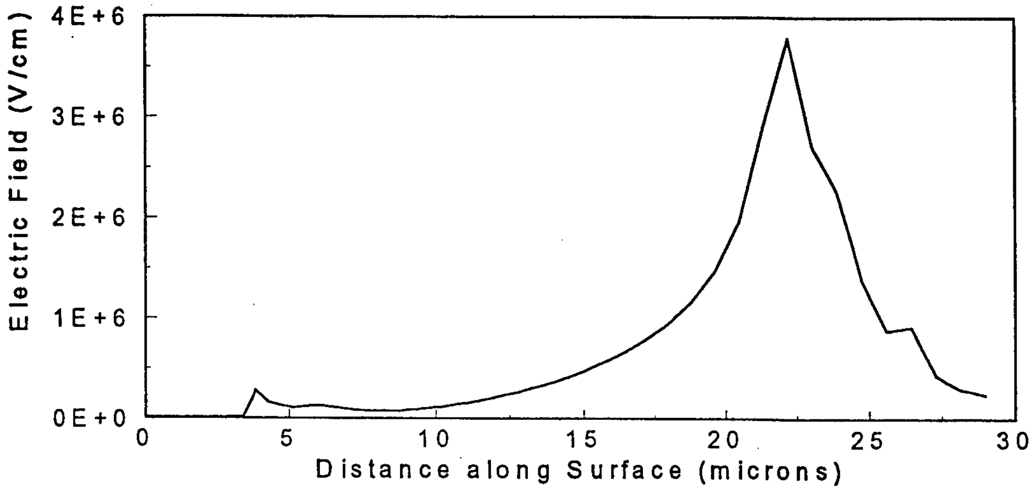

Fig 8 Electric Field Profile in the RESURF layer for a dose of $1x10^{12}$ /cm^2

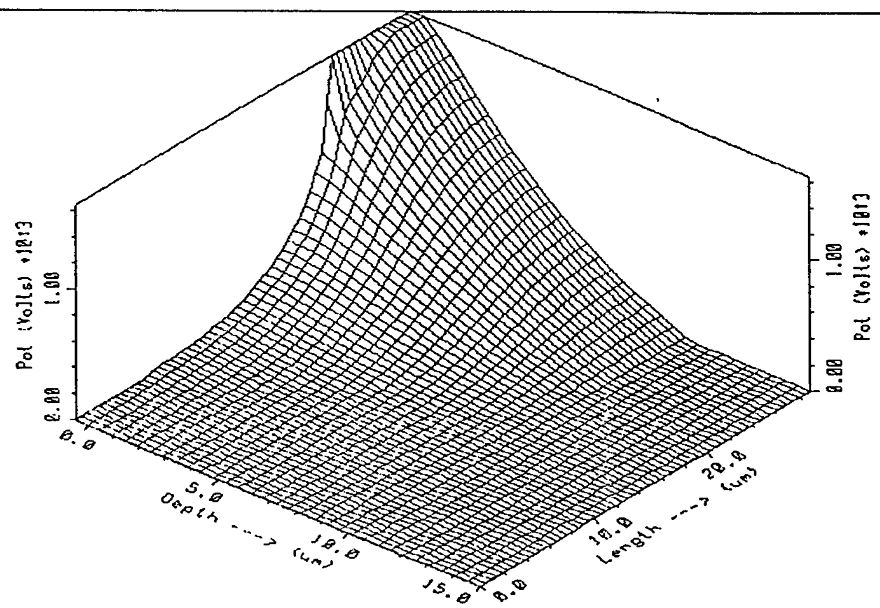

Fig 9 3-D Plot of the Potential distribution in the diode for a dose of $1x10^{12}$ /cm^2

<u>Region 3:</u> At more optimum doses, the field crowding at the anode and the cathode end are comparable. In this case, therefore, a more uniform field profile is obtained in the RESURF layer. Here again, the breakdown occurs at the drain end but if the RESURF length is sufficiently large, then the breakdown can occur at the horizontal $P^{-}N_{res}$ junction and one can achieve the maximum breakdown voltage possible. The potential distributions and the electric field profile for this case (for a dose of $7x10^{12}$ /cm^2) are shown in Fig. 10 and Fig 11.

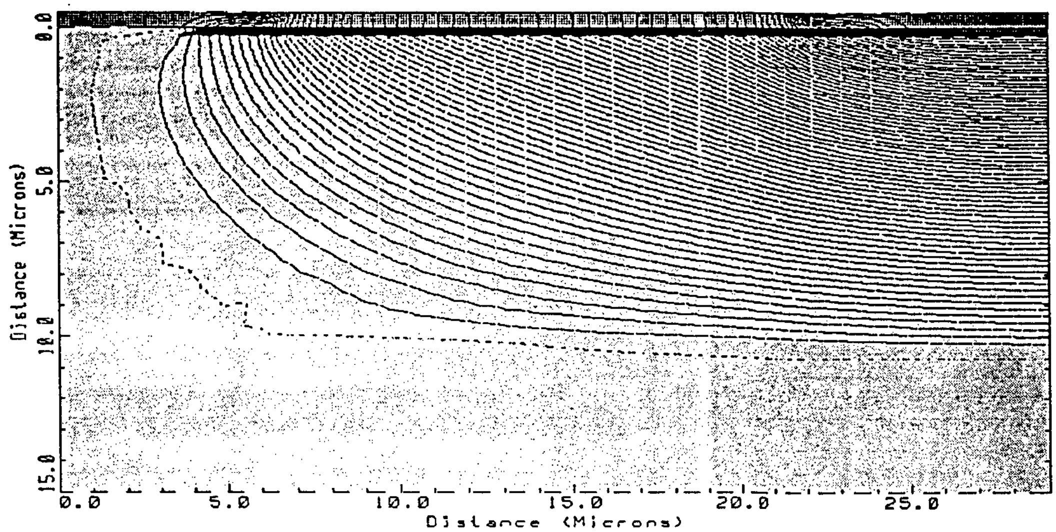

Fig 10 Potential Contours at breakdown for RESURF dose of 7x10^12 /cm^2

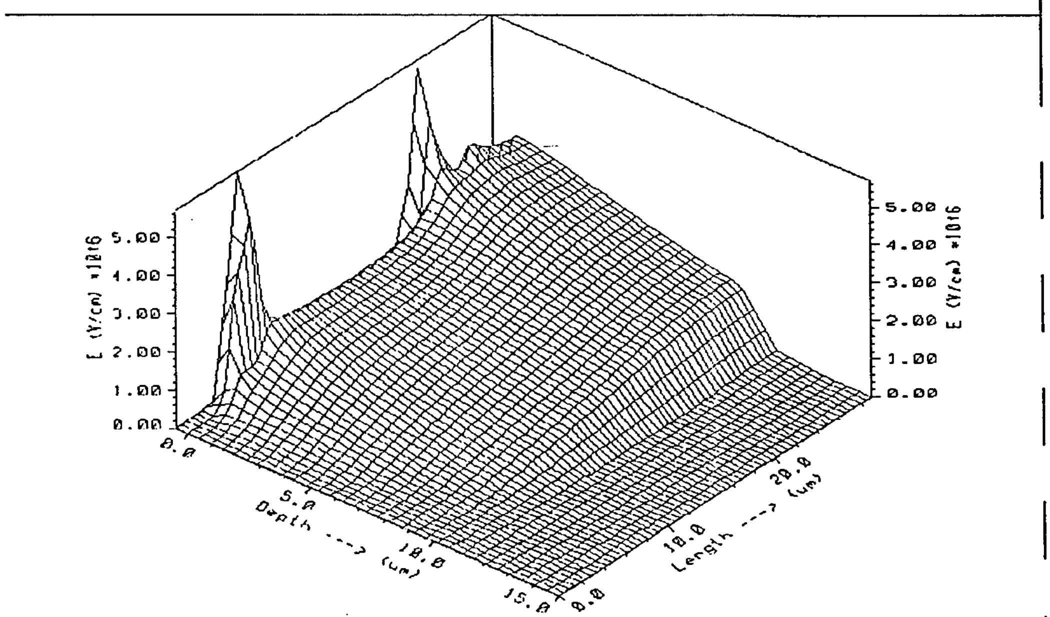

Fig 11 3-D Plot of the Electric field in the diode for a dose of 7x10^12 /cm^2

The 1-D electric field profile at the surface in SiC can be seen in Fig. 12. For this optimum dose, two almost equal peaks are formed at the anode and cathode end. This kind of profile can support a higher breakdown voltage than other profiles seen in previous cases. Fig 13 shows the 3-D potential distribution for this case.

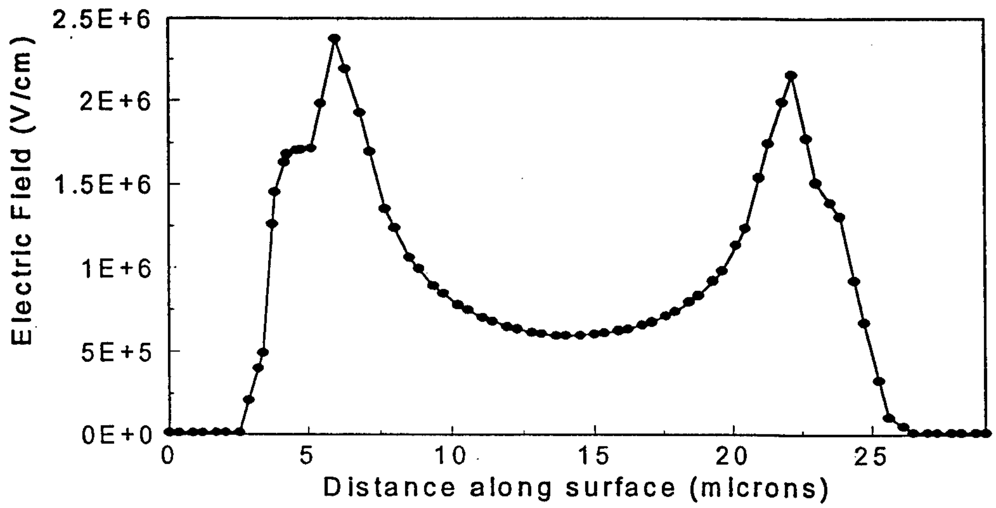

Fig 12 Electric Field Profile in the RESURF layer for a dose of $7x10^{12}$ /cm^2

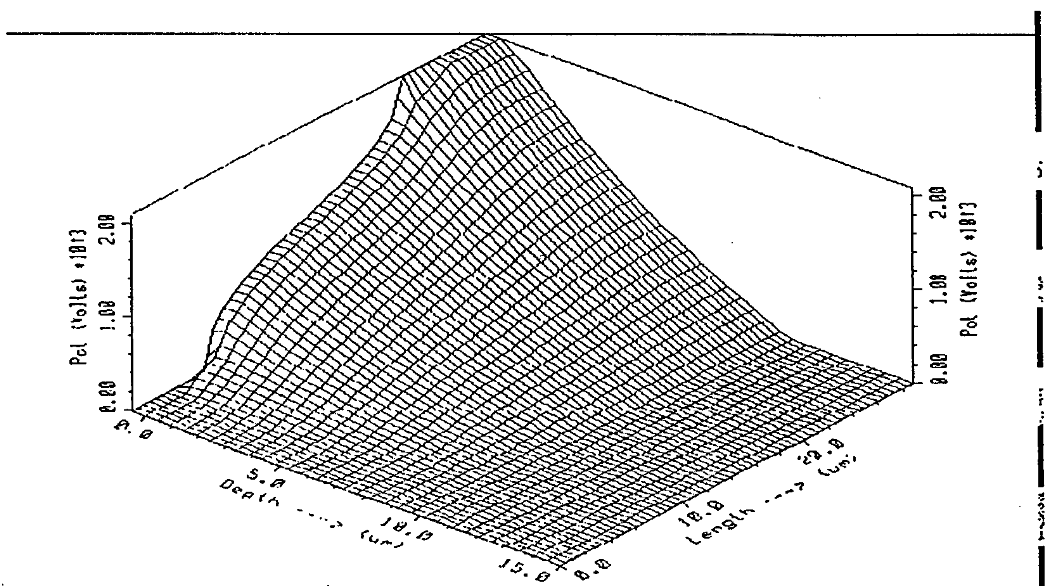

Fig 13 3-D Plot of the Potential distribution in the diode for a dose of $7x10^{12}$ /cm^2

The potential distribution along the substrate at the cathode end is shown in Fig 14. The depletion extends all the way to the epi layer and punches through to the P^+ substrate. Therefore, a higher breakdown voltage can be obtained if a thicker epi layer is chosen. However due to the current unavailability of epi layers thicker than 10 microns, we did not simulate for thicker epi layer devices.

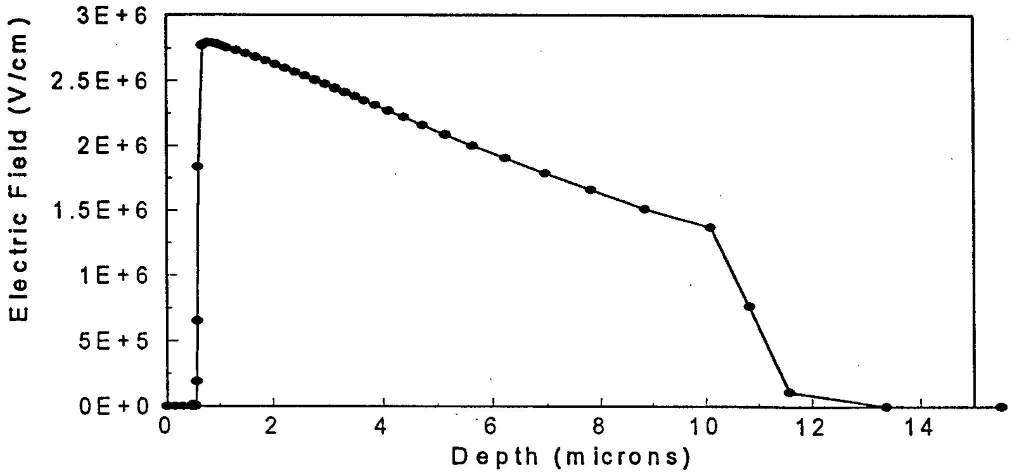

Fig 14 Electric Field Profile along the substrate (cathode end)

The breakdown voltage vs. RESURF layer dose, then follows the curve shown in Fig.15 For very high doses, the breakdown voltage is limited by the breakdown due to field crowding at the anode end and hence is quite low. At intermediate doses, better breakdown voltages are obtained due to more uniform electric field in the RESURF layer. For very low doses, the breakdown is again limited by the field crowding at the cathode end. This is again lower than the ideal parallel plane breakdown though not as low as for high doses.

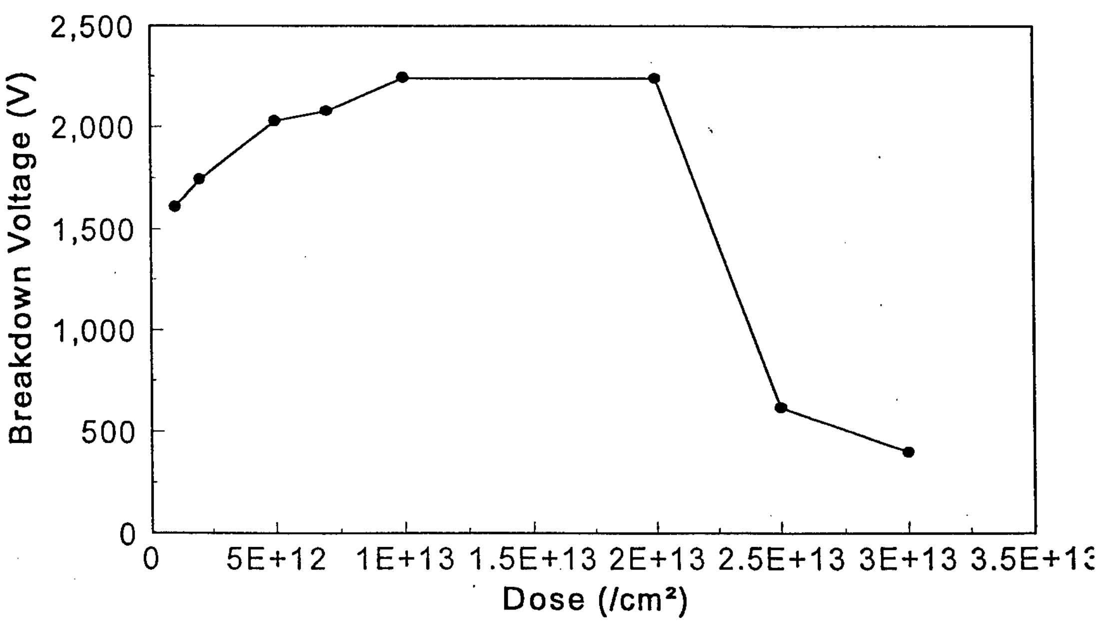

Fig 15 Dose vs. Breakdown Voltage for the single zone RESURF diode

From our simulations, the maximum breakdown voltage that we obtained was 2240V at a dose of 1×10^{13} /cm^2 which is around 94% of the ideal parallel plane breakdown voltage. For comparison, the ideal parallel plane breakdown voltage for the same epi layer doping of 6×10^{15}/cm^3 is around 300V for Si.

Simulations were also performed for different lengths of the RESURF layer. As the length is increased, the breakdown voltage increases linearly till it reaches the ideal parallel plane breakdown voltage, after which it saturates. Further increase in the length of the RESURF layer does not increase the breakdown voltage appreciably. This can be seen from Fig.16, from which the optimum length is found to be 15μ. All the simulations for this were done for the dose of 1×10^{13} /cm^2.

For the dose of 1×10^{13} /cm^2, where maximum breakdown occurs, the breakdown occurs at the cathode end. The breakdown voltage can be expected to be affected by the position of the cathode field plate position. Therefore, we ran simulations for various field plate lengths. The simulation results are shown in Fig. 17. From the simulation results, we find that in this case, the field plate length does not play a critical role in determining the breakdown voltage of the device.

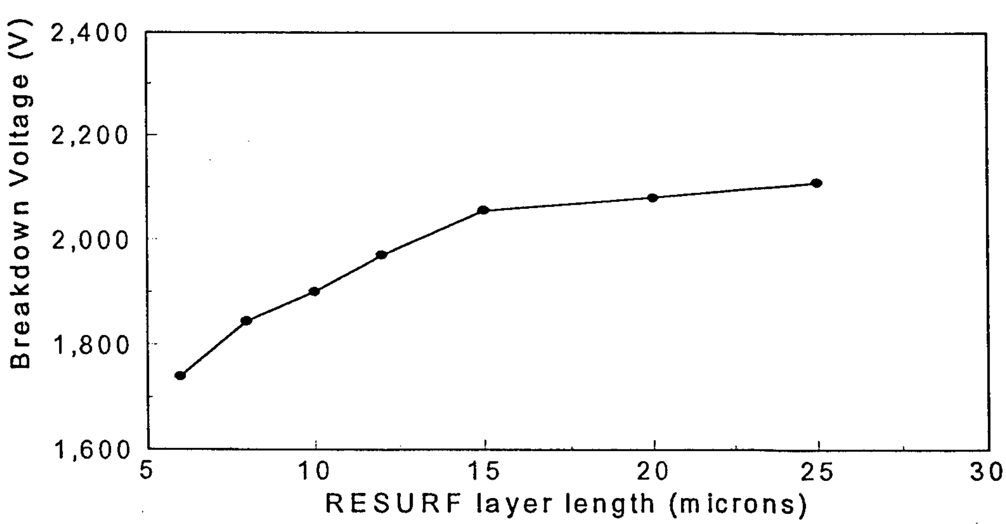

Fig 16 Breakdown Voltage obtained for different RESURF lengths (L_R)

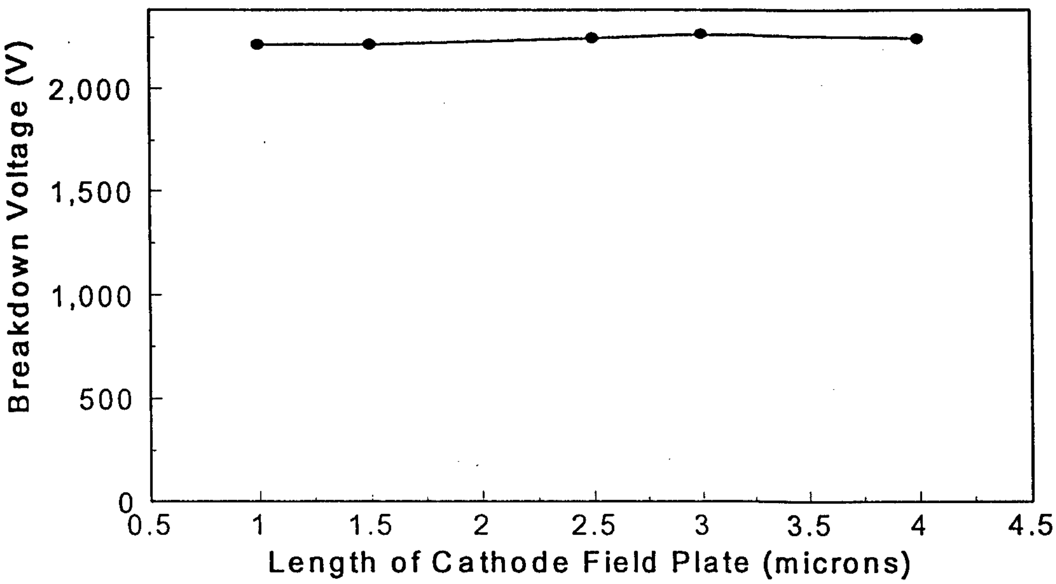

Fig 17 Breakdown Voltage for different Field Plate lengths (L_P)

Another point of concern in fabricating these devices is the electric field in the oxide. Since the critical electric field of SiC is higher than Si, the field in oxide can become quite high and the device might fail due to oxide rupture. The field profile in the oxide is shown in Fig.18 for the dose of 1×10^{13} /cm^2 at the bias of 2240V. The maximum field that we observe in the oxide is around 7×10^6 V/cm.

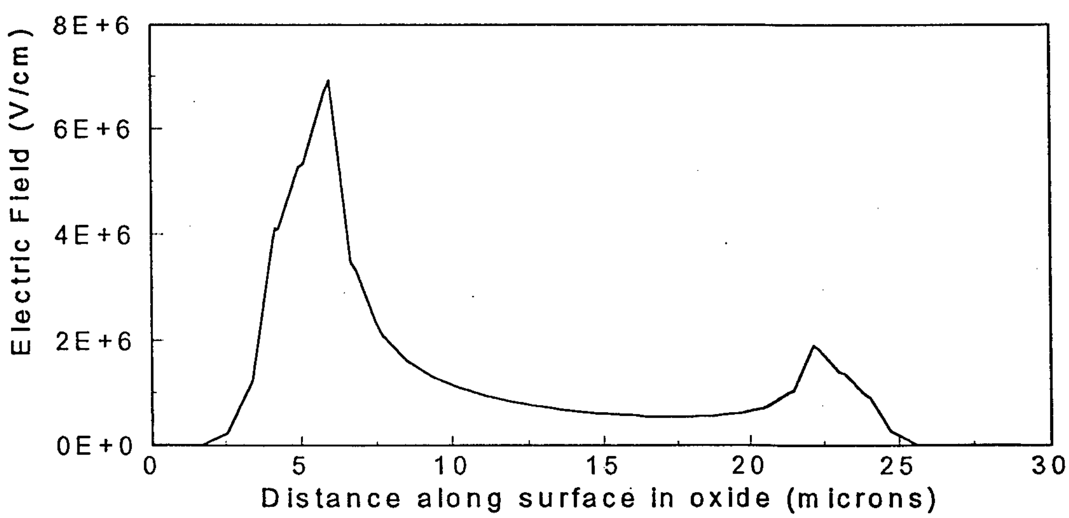

Fig 18 Electric Field in the oxide for the RESURF dose of 1×10^{13} /cm^2 when a voltage of 2240V is applied to the cathode.

Though this field is less than the oxide rupture field, it is still high enough to make these devices unreliable. One of the solutions to this problem is to use an insulator with a dielectric constant higher than that of oxide. For instance, Silicon Nitride has a dielectric constant
of 7.5 as compared to oxide whose dielectric constant is 3.9. This means that a field of 7×10^6 V/cm in oxide would correspond to a field of around 3.7×10^6 V/cm in nitride. The nitride rupture field being the same as that of oxide, this would mean that more reliable devices can be fabricated using nitride rather than oxide. Consequently, simulations were done using nitride as the dielectric and these results are discussed next.

Simulations using Nitride as the dielectric

Simulations were repeated for the structure shown in Fig.1 with nitride in place of oxide. All other parameters were kept the same. The RESURF diode exhibits similar regions of operations as in the oxide case. In region 1, when the dose is very high, breakdown occurs at the anode end due to electric field crowding under the anode. The potential distribution for this case is shown in Fig 19.

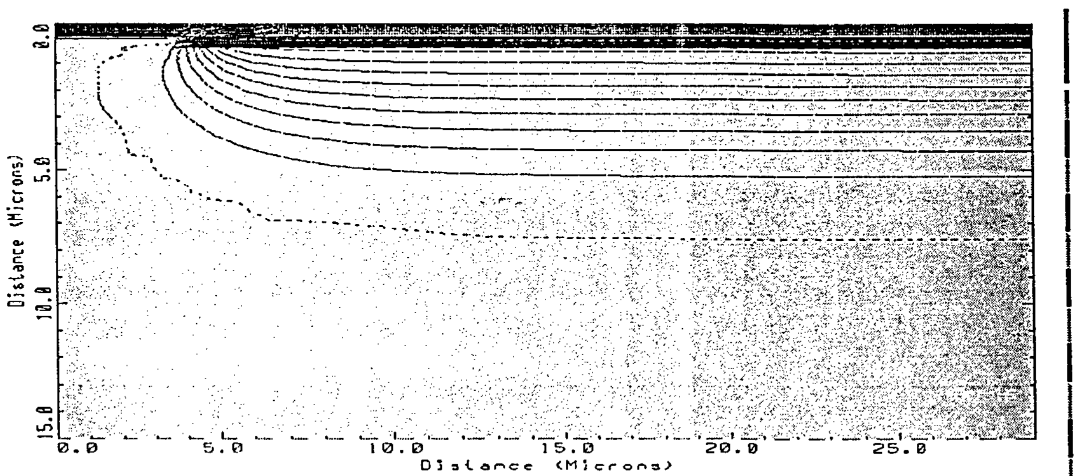

Fig.19 Potential Contours at breakdown for RESURF dose of $3x10^{13}$ /cm^2

The electric field profile in the device and along the surface are shown in Fig. 20 and Fig. 21. A very high peak can be observed in the anode region which is responsible for an early breakdown of the device.

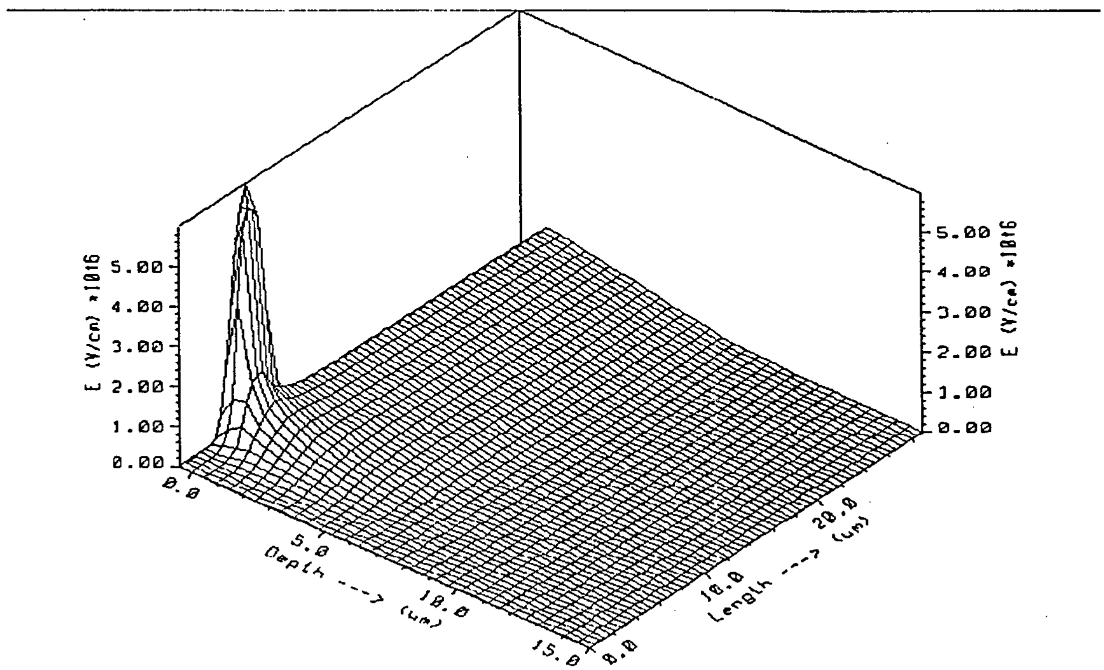

Fig 20 3-D Plot of the Electric field in the diode for a dose of $3x10^{13}$ /cm²

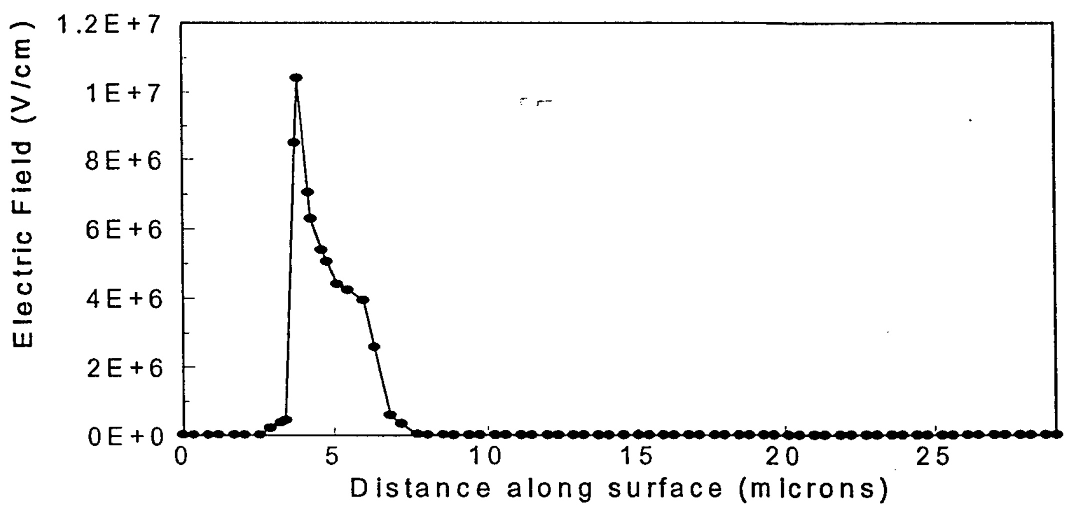

Fig.21 Electric Field Profile in the RESURF layer for a dose of $3x10^{13}$ /cm²

Fig 22 shows the potential distribution in the device and once again we see a large potential drop at the anode end.

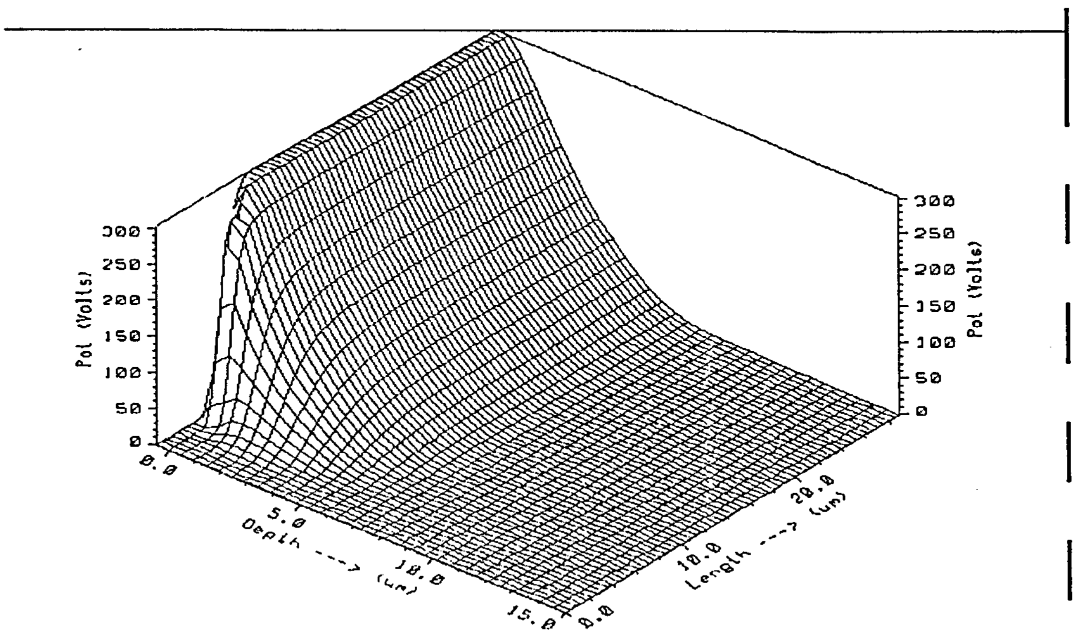

Fig 22 3-D Plot of the Potential Distribution in the diode for a dose of $1x10^{12}/cm^2$

Region 2 shows the other extreme with electric field crowding at the cathode end for a very low dose. The breakdown voltage is again less than optimal as expected. The potential distributions and the electric field distribution in the device are shown in Fig.23 and Fig. 24.

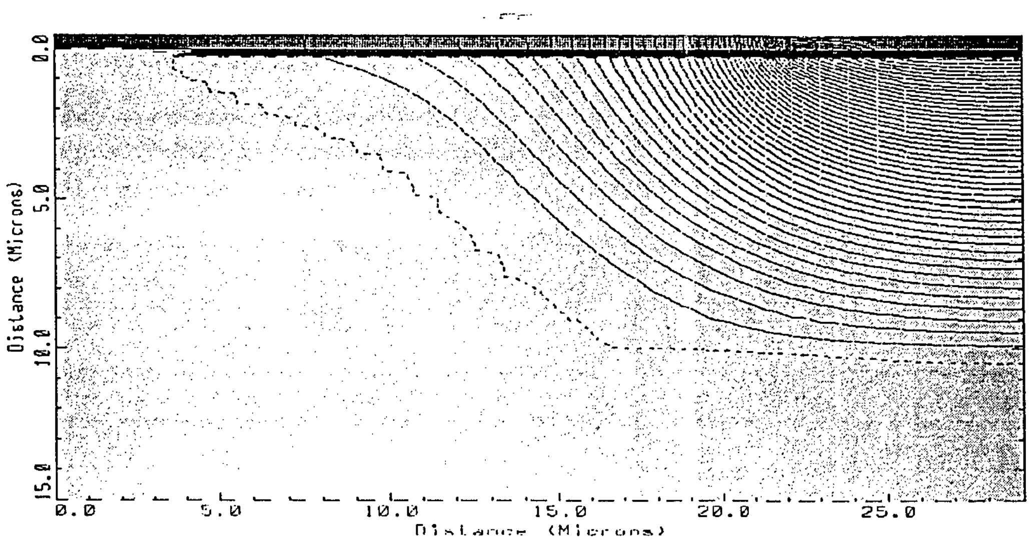

Fig.23 Potential Contours at breakdown for RESURF dose of $1x10^{12}$ $/cm^2$

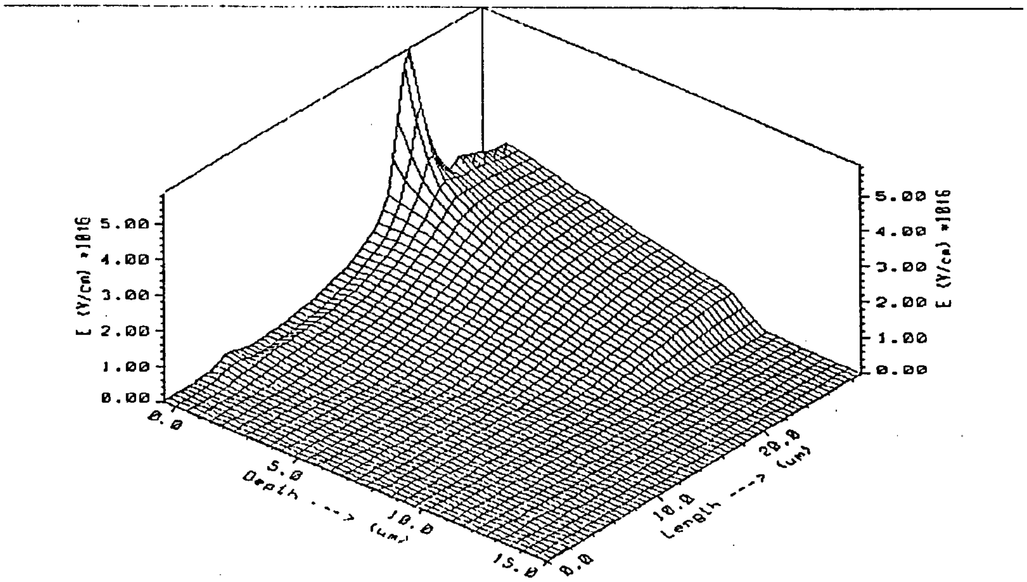

Fig 24 3-D Plot of the Electric field in the diode for a dose of $1x10^{12}$ /cm^2

The 1-D electric field profile for this case is shown in Fig. 25 and the potential distribution in the device is shown in Fig. 26. Both the plots indicate high electric fields at the cathode end which leads to an early breakdown of the device.

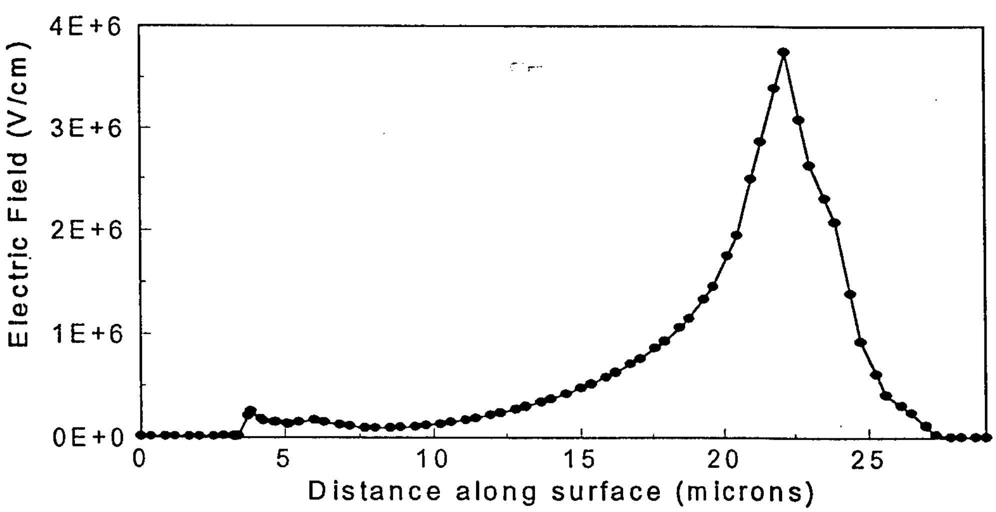

Fig.25 Electric Field Profile in the RESURF layer for a dose of $1x10^{12}$ /cm^2

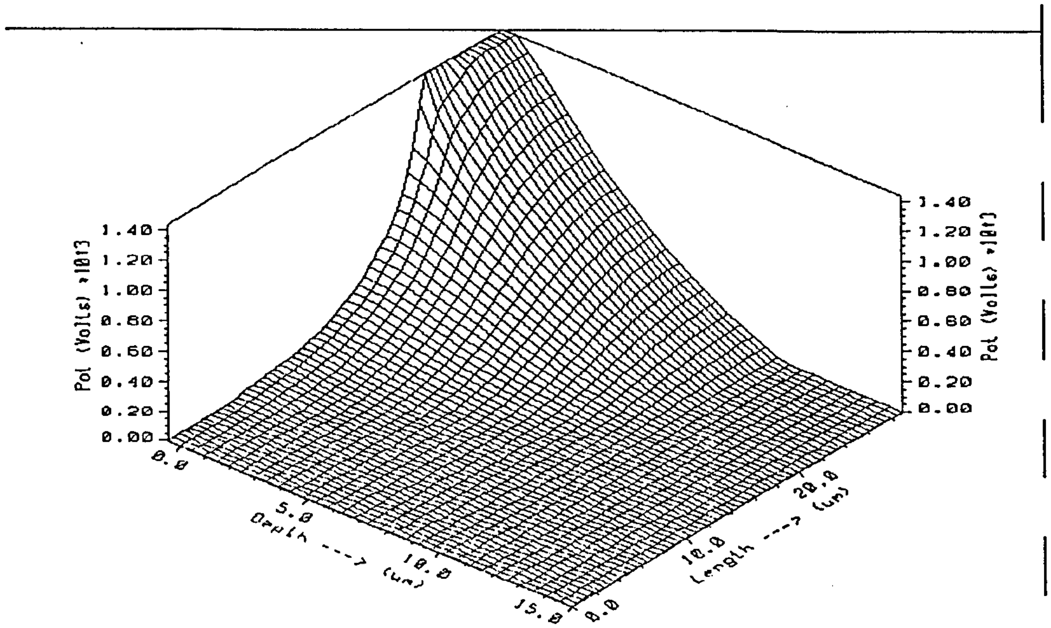

Fig 26 3-D Plot of the Potential distribution in the diode for a dose of $1x10^{12}$ /cm^2

Region 3 corresponds to the optimal case, where the electric field is more uniformly distributed in the RESURF layer. Two peaks of the electric field occur at both the anode and the cathode end. Due to the more uniform electric field profile, the breakdown voltage is higher in this case as explained before. The potential distributions and the electric field profile for this region of operation are shown in the following figures.

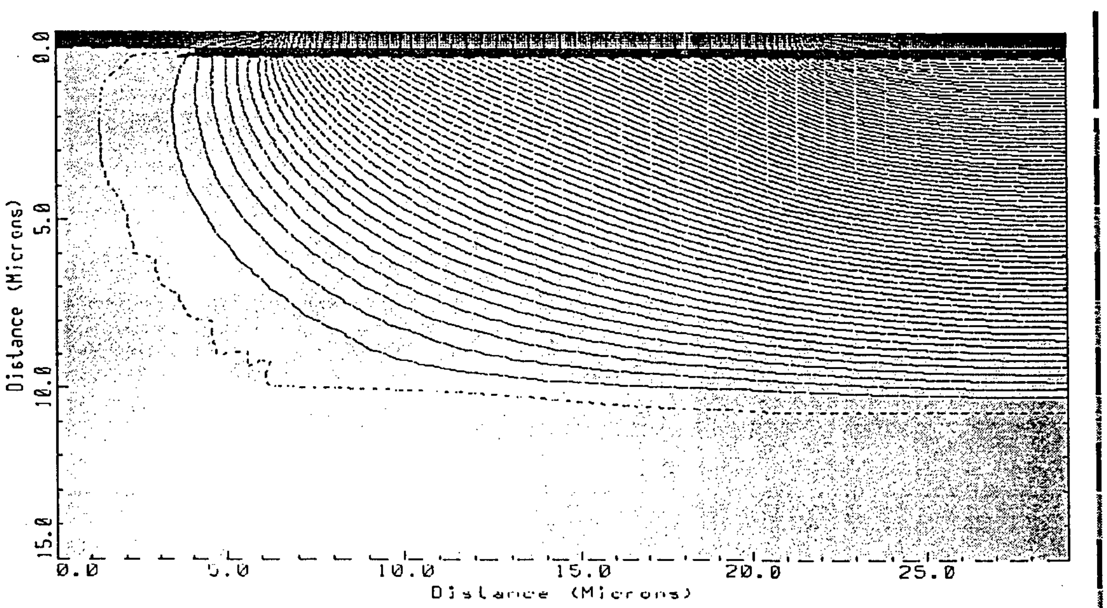

Fig.27 Potential Contours at breakdown for RESURF dose of $7x10^{12}$ /cm^2

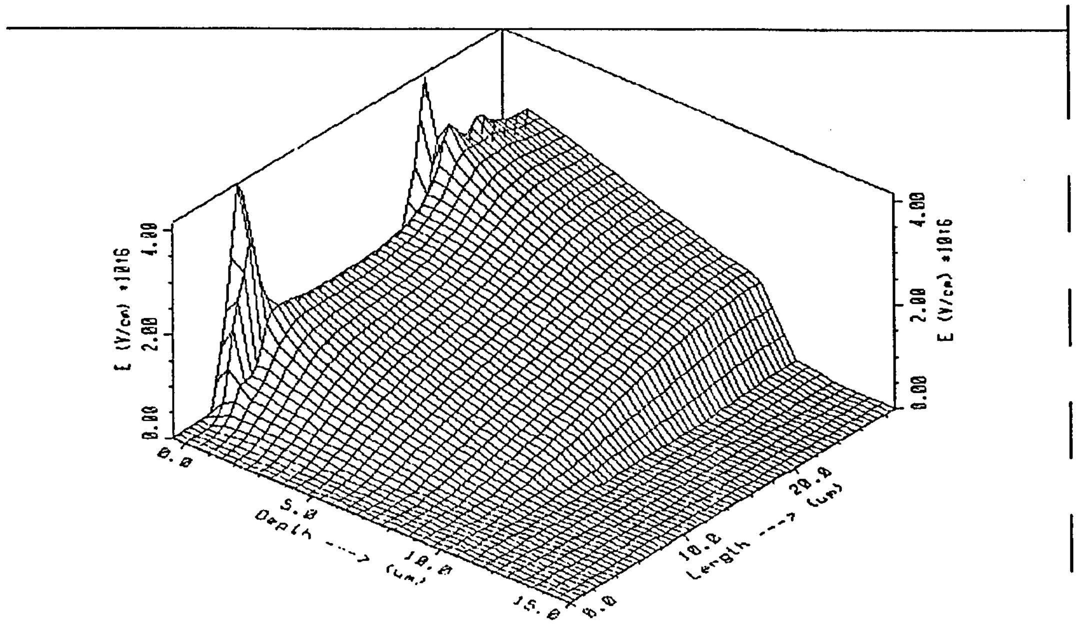

Fig 28 3-D Plot of the Electric field in the diode for a dose of $7x10^{12}$ /cm²

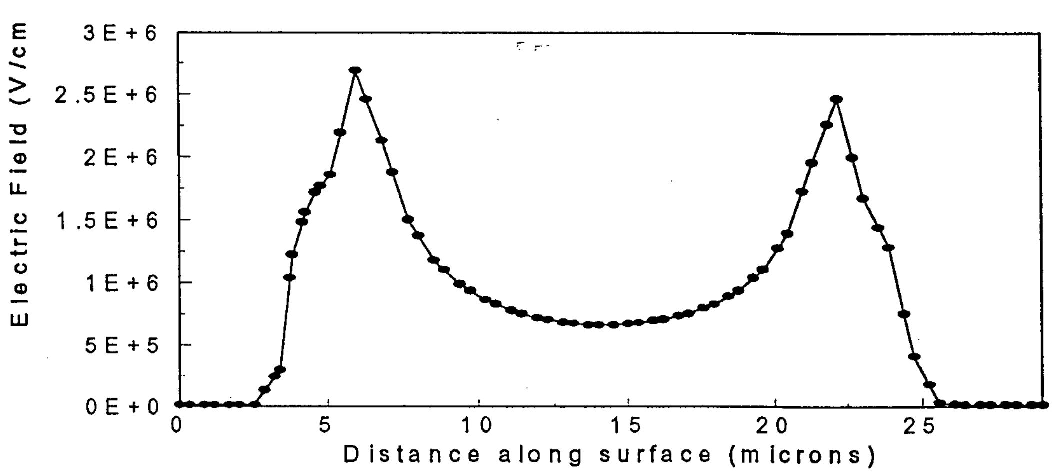

Fig. 29 Electric Field Profile in the RESURF layer for a dose of $7x10^{12}$ /cm²

Both Fig 28 and Fig 29 clearly show 2 electric field peaks at both the anode and the cathode end. As in the oxide case, this kind of profile gives a better breakdown voltage. The potential distribution in the device is shown in Fig. 30 for this case.

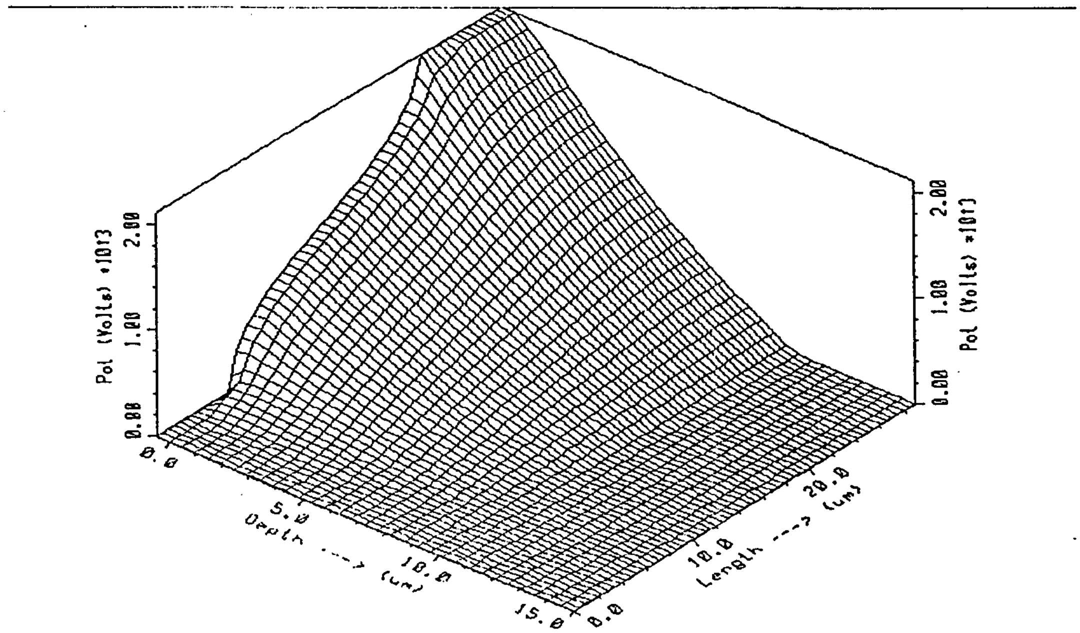

Fig 30 3-D Plot of the Potential distribution in the diode for a dose of $7x10^{12}$ /cm^2

For the nitride simulations, the optimum dose was found to be $7x10^{12}$ /cm^2 which gave the maximum breakdown voltage of 2100V. This is around 150V lesser than the maximum breakdown voltage that was obtained for the oxide simulations. The breakdown voltage for different RESURF doses is shown in Fig. 31.

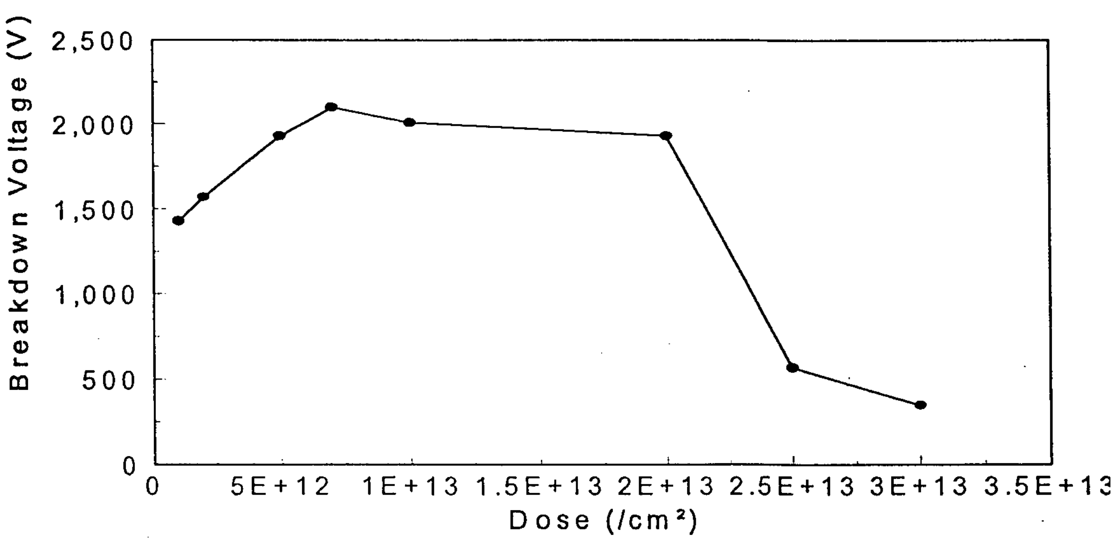

Fig. 31 Dose vs. Breakdown Voltage for the RESURF diode with nitride as dielectric

For the optimum case where we get the maximum breakdown voltage, the corresponding electric field in the nitride is shown in Fig 32.In this case, the maximum electric field in the nitride is less than half the field in the oxide case. The electric field in nitride doesn't exceed 3.5×10^6 V/cm which is much less than the nitride rupture field of 1×10^7 V/cm Therefore, devices made with nitride as the dielectric should turn out to be more reliable than devices made in oxide for very high voltage devices.

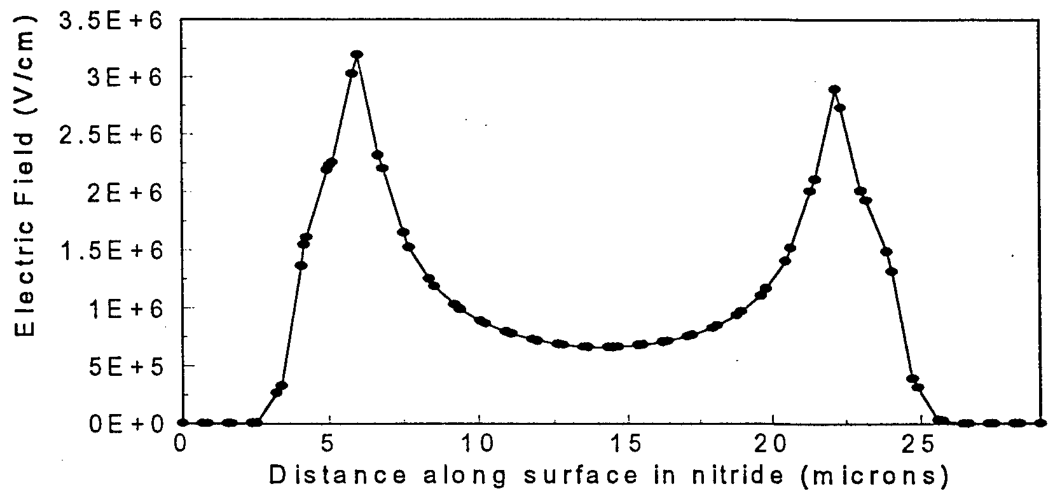

Fig.32 Electric Field in nitride for a RESURF dose of $7x10^{12}$ /cm^2

Conclusions

Extensive numerical simulations were performed to study the breakdown voltage of the single zone RESURF diode with both oxide and nitride as the dielectric. For the oxide, we obtained the maximum breakdown voltage of 2240V which was at a dose of 2×10^{13} /cm^2. The maximum electric field at this dose in the oxide was around 7×10^6 V/cm. This is a reasonably high electric field, even though it is less than the oxide rupture field of 1×10^7 V/cm. This could possibly make devices unreliable. To solve the problem of high fields in oxide, we decided to replace the oxide with nitride which has a lower dielectric constant. Simulations with nitride as the dielectric indicate the maximum electric field in nitride to be less than 3.5×10^6 V/cm, which is much less than the nitride rupture field of 1×10^7 V/cm . The maximum breakdown voltage that we obtained for the nitride case was 2100V at a dose of 7×10^{12} /cm^2 . For both oxide and nitride cases, we obtained a good range (7×10^{12} /cm^2 - 2×10^{13}/cm^2) of dose where the breakdown voltage is quite high (2000V and above). A high breakdown voltage at a high dose of 2×10^{13}/cm^2 implies that devices like RESURF MOSFETs can be fabricated, which will exhibit a high breakdown voltage and a low specific on-resistance.

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